CHARGE INDEPENDENCE AND CHARGE SYMMETRY

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ABSTRACT

Charge independence and charge symmetry are approximate symmetries of nature, violated by the perturbing effects of the mass difference between up and down quarks and by electromagnetic interactions. The observations of the symmetry breaking effects in nuclear and particle physics and the implications of those effects are reviewed.

1. Introduction

This paper is concerned with charge independence and charge symmetry which provide powerful tools in organizing and describing the multiplet structure of hadrons and nuclei[1,2]. These symmetries are imperfect; diverse small but interesting violations have been discovered. For reviews see Refs. [3]-[7].

The emergence of Quantum Chromodynamics, QCD, as the underlying theory of the strong interaction has added a new impetus to this field. QCD indicates that each and every violation of charge independence or charge symmetry has its origin in the different masses of the up and down current quarks and in the electromagnetic interactions between the quarks. Thus the small imperfections of these symmetries provide a unique opportunity to study the relation between quark mass differences and hadronic and nuclear observables. A prominent example is that the positive value of $m_d - m_u$ causes the neutron to be heavier than the proton in contrast with the result expected from electromagnetic effects. This review is concerned with the evidence that the light quark mass difference m_d-m_u plus electromagnetic effects accounts for charge independence and charge symmetry breaking, CSB, in systems of baryon number ranging from 0 to 208.

Let us define the terms charge independence and charge symmetry. Consider the QCD Lagrangian in the limit that m_d and m_u vanish and ignore electromagnetic effects. In that case, the u and d quarks are equivalent and can be treated as an

isodoublet $\binom{u}{d}$. One may introduce the isospin operators $\vec{\tau}$ with

$$[\tau_i, \tau_j] = i\ \epsilon_{ijk}\tau_k, \tag{1}$$

$$\tau_3|u >= |u >, \qquad \tau_3|d >= -|d > . \tag{2}$$

The total isospin for a system of quarks is then

$$\vec{T} = \Sigma_i \vec{\tau}(i)/2. \tag{3}$$

In the present limit,

$$[H, \vec{T}] = 0. \tag{4}$$

This vanishing is the invariance under any rotation in isospin space and known as charge independence or isospin symmetry. Charge symmetry is related specifically to a rotation by π about the y-axis in isospin space:

$$[H, P_{cs}] = 0, \tag{5}$$

with

$$P_{cs} = e^{i\pi T_2}, \tag{6}$$

if the positive z-direction is associated with positive charge. P_{cs} converts u quarks into d quarks and vice versa:

$$P_{cs}|u >= -|d >, \quad P_{cs}|d >= |u > . \tag{7}$$

Ref. [6] was the first to use this quark based definition of charge symmetry.

A violation of charge symmetry implies that charge independence is broken; but the converse is not true. For example, the operator $\tau_3(1)\tau_3(2)$ between two nucleons preserves charge symmetry.

It is hadrons, not quarks, that are observed, so it is reasonable to ask how is the quark operator $\vec{T}$ related to hadronic isospin operators. Isospin, like charge, is an additive quantum number, so the isospin operator can be expressed equivalently in terms of quarks or hadrons. This means that the hadronic implications of charge independence or charge symmetry can be understood from the quark content of the systems involved. For example, charge symmetry predicts the equality of the $\Lambda(uds)-p(uud)$ and $\Lambda(uds) - n(udd)$ interactions.

But there are other serious concerns about the application of these quark concepts to reality. The first problem is that quarks are confined and can not be isolated. This means that a specific definition of the term "quark mass" is required. It is natural to speak of the mass that appears in the Lagrangian of QCD; this is the current quark mass. Evaluations of these masses have been made by many authors. For

example, Gasser and Leutwyler[8] use QCD sum rules for the divergence of the axial vector current along with current algebra and pseudoscalar meson masses to obtain $m_u = 5.1 \pm 1.5$ MeV and $m_d = 8.9 \pm 2.6$ MeV (evaluated at a momentum transfer scale of 1 GeV). The individual quark masses have an error of $\pm 30\%$, while the ratio m_d/m_u is more accurately determined as 1.76 ± 0.13 [8]. See also Ref. [9]. The scale dependence arises because the bare masses are replaced by physical ones by the necessary renormalization procedure. But the physical masses are not measured, so that it is necessary to choose an arbitrary kinematic reference point to define the physical quark masses.

A second problem is that the ratio $\frac{m_d}{m_u} \approx 2$ seems to strongly violate the symmetry. Thus one may wonder why any trace of charge independence would remain in nature. However each of m_d and m_u is less than 10 MeV, and these current quark masses are replaced by constituent masses for confined quarks. In this case, the mass of each of the three quarks in the nucleon supplies about one-third of the nucleon mass, which is much larger than the current quark mass. Various strong interaction effects, every one of which respects charge independence, are thought to cause this relatively large value. Thus the ratio of the down to up constituent quark mass is very close to unity despite the fact that the ratio of the current quark masses is about two! Explanations of the origin of this unity fall into two categories. The first is dynamical symmetry breaking, in which non-perturbative quark-pair creation and gluon-exchange effects cause the vacuum to reduce its energy by acquiring a non-zero expectation value (vacuum condensate) of the quark field operator $\overline{\psi}(0)\psi(0)$. In that case, the color force must lead also to a quark self-energy that plays the role of a quark mass. Numerical calculations starting with the chiral limit ($m_d = 0, m_u = 0$) show that dynamical symmetry breaking generates quark masses consistent with the large constituent quark masses[10,11]. In the chiral limit, the resulting constituent masses of the up and down quarks are the same. One can also include the small current quark masses with the result[10,11] that the small nature of the mass difference between the up and down current quarks is retained by the resulting constituent quarks, and is small compared with the sum of the constituent masses.

In constituent quark models the effects of confinement can also yield contributions to the quark mass because the separation between a confining potential and a quark mass is a matter of choice. Other models are that of the MIT bag and the non-topological soliton with massless or very light quarks. Then the average quark kinetic energy (of order 350 MeV) acts as a quark mass in many matrix elements. In any case, the confining potential and kinetic energy of massless quarks are the same for up and down quarks. The average constituent quark mass, whether arising from dynamical symmetry breaking or confinement, is dominated by charge symmetric effects and is about a third of the proton mass. In all models of QCD that involve quarks, any small difference between up and down quark constituent quark masses is caused by a difference between the corresponding current quark masses.

A final comment about quarks concerns the term "accidental symmetry", intro-

duced by Gross, Treiman and Wilczek[12], to describe isospin symmetry. The term "accidental" arises because charge independence is well-maintained in nature even though the current quark ratio m_d/m_u is quite large. But isospin symmetry naturally results from the dependence of observables on constituent quark masses $m(\text{const})$ which satisfy $m_d(\text{const})/m_u(\text{const}) \approx 1$ as an inevitable consequence of dynamical symmetry breaking inherent in QCD. Furthermore, van Kolck[13] has used the chiral symmetry of QCD to show that charge independence breaking effects are small; of the order of $(m_d - m_u)/m_\rho$ where $m_\rho \approx 780\,MeV$ is the mass of the rho meson. (A possible exception is π^0-nucleon scattering for which charge dependence **is** governed by the ratio $(m_d - m_u)/(m_d + m_u)$ of current quark masses[13].) Thus we believe that progress in understanding non-perturbative aspects of QCD is now sufficient to say that the use of the term accidental symmetry is a misnomer. The approximate validity of charge independence is understood.

The remainder of this article is concerned first with the quark mechanisms behind charge independence and its breaking, Sect. 2. The mass difference between the up and down quarks leaves its imprint on many hadronic matrix elements. This allows the computation of many nuclear effects that break charge independence. Sect. 3. is concerned with the diverse sets of new experimental information. Several significant observations have been made, but the interpretation of some other experiments is clouded by the presence of Coulomb effects. A summary and discussion of the directions that future work could take is given in Sect. 4.

2. Mechanisms of charge independence and charge symmetry breaking

The breaking of charge independence and charge symmetry occurs via the positive value of $m_d - m_u$ and, by quark electromagnetic effects. How are these effects realized in nature? We discuss the present ideas and argue that, at present, the most successful procedure is to use quark effects to understand hadronic masses and meson-mixing. Then nucleon-nucleon interactions are described in terms of meson exchange models which include the effects of hadronic charge independence breaking mandated by the quark effects.

2.1 Mass splittings of hadronic isospin multiplets

There are many quark models of baryon and meson structure[1]. In those models one simply evaluates the consequences of the quark masses and of the electromagnetic interactions. A common explanation of the mass differences within isotopic multiplets has emerged. This is important since an old and difficult issue — "the sign of the isotopic mass splitting puzzle" was resolved by the use of quarks. Before quark physics was introduced, the only definite mechanism for the breaking of charge independence was the electromagnetic interaction. Charge independence implies that the neutron and proton mass are equal. But naive estimates and sophisticated evaluations[14] based on the electromagnetic interaction gave the inevitable result that a charged particle

is heavier than its neutral partner. But nature does not follow this recipe: $m_n > m_p$ and $m_{K^0} > m_{K^-}$, while $m_{\pi^0} < m_{\pi^+}$; furthermore $m_{\Sigma^+} < m_{\Sigma^0} < m_{\Sigma^-}$. This riddle is solved by realizing that we should not arrange multiplets by their electric charge but by their u-d flavor. If two hadrons are related by replacing a u quark by a d quark, the d-rich system is heavier. This holds for all mesons and baryons*for which a comparison is possible. See Table 1 of Ref. [7]. Thus the positive value of $m_d - m_u$ is more important numerically than the electromagnetic effects.

The above discussion is qualitative, but the details of many complicated computations have been reviewed in Ref. [6]. The positive nature of $m_d - m_u$, as corrected by electromagnetic effects, accounts for the mass differences within hadronic multiplets even though the specific values vary from model to model.

2.2 Mixing Hadrons

In the absence of charge independence breaking the neutral mesons of u-d flavor are states of pure isospin, given schematically as

$$|I=1>=\frac{1}{\sqrt{2}}|u\bar{u}>-\frac{1}{\sqrt{2}}|d\bar{d}>, \qquad |I=0>=\frac{1}{\sqrt{2}}|u\bar{u}>+\frac{1}{\sqrt{2}}|d\bar{d}>. \tag{8}$$

The isospin of a state is determined by the final states obtained via strong decay processes, i.e. 2π for I=1 and 3π for I=0. However, the perturbing effects of the quark mass difference and electromagnetic effects cause the states to mix. For example, the quark mass contribution to the QCD Hamiltonian, H_m

$$H_m = m_d \bar{d}d + m_u \bar{u}u, \tag{9}$$

gives a mixing matrix element of the form

$$< I=1|H_m|I=0>= m_u - m_d, \tag{10}$$

which is negative. Electromagnetic effects also enter, as we shall discuss.

In general, neutral mesons are mixtures of I=0 and I=1 states, with the largest mixing occurring when the unperturbed states are close in mass. Thus the best studied case is that of $\rho^0 - \omega$ mixing. The case of $\pi^0 - \eta - \eta'$ mixing is handled in an analogous fashion, but the octet-singlet SU(3) mixing between the η and the η' causes a complication. This is reviewed in Sect. 3.3.12 of Ref. [6].

Here we concentrate on $\rho^0 - \omega$ mixing which is the strongest and most prominent observation of charge symmetry breaking. The effects of this matrix element are observed[16,17] in the annihilation process $e^+e^- \to \pi^+\pi^-$. The relevant diagrams are shown in Fig. 1 and the huge signal arising from the small widths of the ω-meson is displayed in Fig. 2. The mixing matrix element has been extracted[18] to be

$$< \rho^0|H|\omega >= -4520 \pm 60 \text{ MeV}^2. \tag{11}$$

*The $\Sigma_c^0(ddc)$ may be slightly less massive than the $\Sigma_c^+(udc)$, but the uncertainty in the Σ_c^+ mass is ± 3.1 MeV[15] which is large in the present context.

Figure 1: Amplitudes for $e^+e^- \to \pi^+\pi^-$.

This matrix element is expressed in units of mass^2, because the observable is related to the self-energy that appears in the Klein-Gordon equation governing meson propagation, so the meson states are normalized as $< \vec{p}, \alpha|\vec{p}\,', \alpha >= 2(\vec{p}\cdot\vec{p}\,'+m_\alpha^2)(2\pi)^3\delta(\vec{p}-\vec{p}\,')$. If one removes the momentum-conserving delta function from the normalization, the states can be normalized to unity e.g. $< \rho\|1\|\rho >= 1$. In this basis, the mixing matrix element can be expressed as $< \rho^0\|H\|\omega >=< \rho^0|H|\omega > /(m_\rho + m_\omega) \approx 2.9$ MeV.

The extracted matrix element $< \rho^0|H|\omega >$ includes the effect of the electromagnetic process depicted in Fig. 3. The quantities f_ρ and f_ω have been determined from the processes $e^+e^- \to \rho, \omega \to e^+e^-$. The most recent analysis[19] gives $< \rho^0|H_{em}|\omega >= 640 \pm 140$ MeV^2 so that the strong contribution ($H = H_{str} + H_{em}$) is given by $< \rho^0|H_{str}|\omega >= -5160 \pm 150$ MeV^2. Another notable feature is that the electromagnetic contribution to the $\rho\omega$-mixing self-energy is of the form

$$\Pi^{em}_{\rho\omega}(q^2) \sim \frac{e^2}{f_\rho f_\omega}\,\frac{1}{q^2} \tag{12}$$

where q^2 is the square of the vector meson four-momentum.

Figure 2: $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$. These are the data introduced and summarized in Ref. [16].

Figure 3: Electromagnetic contribution to ρ^0-ω mixing.

The question of whether the consequences of this significant mixing has any observable consequences in nucleon-nucleon scattering and nuclear physics is discussed at the end of the Sect. 2.3.

Baryons can also mix. The oldest example[20,21] is that of $\Lambda - \Sigma^0$ mixing. See the review, Ref. [22]. In first-order perturbation theory

$$|\Lambda> \;=\; |uds, I = 0 > +\alpha|uds, I = 1 > \tag{13}$$

$$|\Sigma^0> \;=\; -\alpha|uds, I = 0 > +|uds, I = 1 >, \tag{14}$$

where

$$\alpha = \frac{< uds, I = 1|H|uds, I = 0 >}{(M_\Lambda - M_{\Sigma^0})}. \tag{15}$$

The use of SU(3) symmetry[20] gives $\alpha = -0.013$, and the quark model of Ref. [21] gives $\alpha = -0.011$, so the mixing matrix element is about 1 MeV. The charge dependent operator must connect the (ud+du) of the Σ^0 with the (ud-du) of the Λ, so the quark mass and kinetic energy difference, and Coulomb interaction do not contribute.

The one gluon exchange interaction which causes the $\Lambda - \Sigma^0$ splitting has a charge dependence arising from its dependence on the quark masses. An order of magnitude estimate then is that $|\alpha| \approx \frac{m_d - m_u}{\bar{m}} \approx 3.3MeV/340\,MeV \approx 0.01$ where the numerator is from Ref. [7] and the denominator is a typical constituent quark mass.

Karl[23] and Henley & Miller[24] have studied the influence of $\Lambda - \Sigma^0$ mixing on the beta decays of $\Sigma^\pm$ to the Λ. The decay rates are known[15] to about 5% for the Σ^- but to about 25 % for the Σ^+, with about a two standard deviation difference between central values. However, such a difference arises from effects of the $\Sigma^\pm$ mass differences on the phase space. Phase space effects can be calculated precisely and are not interesting. However the effect of $\Lambda - \Sigma^0$ mixing is predicted to cause a substantial $\approx 6\%$ difference between the squares of the axial vector matrix elements. Thus Karl and Henley & Miller suggest that improved experiments at about the 1% level in the ratio of the decay rates could clearly observe the effects of baryon mixing. A similar mixing is expected for the charmed, bottom, and top versions of the Λ and Σ baryons with charge symmetry breaking effects exhibited in their beta decays.

2.3 Two nucleon scattering: quark models and meson exchange models

There have been a number of calculations using non-relativistic quark and bag models to compute nucleon-nucleon scattering[25] and some of these have been applied to compute charge independence breaking of the nucleon-nucleon scattering lengths. The main motivation for using the quark model is to gain a better understanding of the nucleon-nucleon short-ranged repulsion. This, in present quark models, arises from the quark Pauli principle and from the gluon exchange hyperfine interaction. Then the charge independence breaking can be computed directly in terms of the mass difference between composite quarks and electromagnetic effects.

Some of the quark models that are most successful in reproducing observed phase shifts use the resonating group model (RGM) in which the six-quark wave function is an antisymmetrized product of six single quark wave functions. This approach has been criticized by Miller[26] who argued that the inclusion of gluon degrees of freedom cause the exchange terms introduced by the antisymmetrizing operator to vanish.

Nonetheless, quark models can be used to provide reasonable descriptions of the nucleon-nucleon phase shifts if the long-range effects of π and σ exchange between nucleons are also included. Brauer, Faessler and Henley [27] used the RGM to compute the strong interaction contribution to the difference between the nn and pp scattering lengths, a^N_{nn}-a^N_{pp}. Charge symmetry breaking contributions from the one-gluon (magnetic) and quark kinetic energy were included. These two mechanisms tend to have cancelling effects, so that the resulting charge symmetry breaking is small: a^N_{pp}-$a^N_{nn} =$ 0.5 fm. See also Wang, Wang and Wong[28] who find that the influence of quark effects on charge independence breaking are highly model dependent. Six-quark bag models have also been used to compute charge independence breaking effects. The results of Koch and Miller[29] for a^N_{pp}-a^N_{nn} are similar to those of Ref. [27], but depend strongly on the model parameters.

The principal finding is that the quark-model effects responsible for the "hard" core of the nucleon-nucleon interaction harbor only small charge independence breaking effects. It is difficult to precisely say how small the effects are because of the strong model dependence of current treatments. Instead it is natural to look for charge independence and charge symmetry breaking arising from effects of longer range. Thus the remainder of our discussion employs meson exchange models.

There has been much discussion of how meson exchange leads to the breaking of charge independence; see the reviews [4]-[6]. The longest range force arises from the one pion exchange potential (OPEP), which also supplies significant breaking of charge independence. This is due to the relatively large mass difference. $\frac{m_{\pi^\pm}-m_{\pi^0}}{m_{\pi^0}} \approx 0.04$. One might worry about including the charge dependence of the coupling constants for neutral (g_0) and charged (g_c) pions. However $g_0^2 = g_c^2$ to better than about 1%, according to recent phase shift analyses of Bugg and Machleidt[30] and the Nijmegen group[31]. The quark model predictions for the charge dependence of the coupling constants are reviewed in Ref. [6]; there is no consensus on the results.

One must also include the effects of the π mass difference in the two pion exchange potential (TPEP). Henley and Morrison[32] were the first to do that. Similarly one may include the effects of isotopic mass differences of heavier mesons and the baryons which appear in intermediate states. Those effects are substantially smaller than the one already mentioned.

Another mechanism involves the two–boson exchange force that arises when one of the bosons is a photon. The pion is the lightest meson so, of these, the $\pi\gamma$ exchange leads to the longest range force and was expected to be the most important. Early calculations were done in the static limit, and later calculations[33,34] are not in the refereed literature or have been criticized in Ref. [5].

It is natural to study the mechanisms mentioned here by predicting nucleon-nucleon scattering observables[35]. The information available is limited mainly to the ^{1}S$_0$ channel[6], although there are some new results. The Nijmegen group[36] has obtained a multi-energy partial wave analysis of all nucleon-nucleon scattering data for laboratory kinetic energies below 350 MeV. An accurate determination of all phase shifts and mixing parameters has been obtained. A charge dependent and charge asymmetric nucleon-nucleon potential has been recently fit to these data by Wiringa et al[37]. The charge independence breaking arises from the effect of the pion mass differences and from phenomenological modifications of the shorter range forces required to reproduce the data. The charge asymmetry is obtained by allowing the strengths of the central S=0, T=1 nn and pp forces to differ in a way that agrees with the low energy nucleon-nucleon scattering data. A different technique is to use the nucleon-deuteron break up reactions which allows the determination of a set of nn, np and pp ^{3}P$_j$ phase shifts[38]. This does not yield a unique determination of these phases[39].

a) ^{1}S$_0$ scattering lengths

We discuss charge independence breaking of the nucleon-nucleon scattering lengths in the $^1S_0$ channel to illustrate how the various mechanisms mentioned above really work.

Charge independence, $[H, \vec{T}] = 0$, imposes the equalities of the nucleon-nucleon scattering lengths $a_{pp} = a_{nn} = a_{np}$. But electromagnetic effects are large and it is necessary to make corrections. The results are analyzed, tabulated and discussed in Ref. [6] and updated here in Sect. 3.1; see Table 3. These are

$$\begin{aligned} a_{pp}^N &= -17.3 \pm 0.4 \text{ fm} \\ a_{nn}^N &= -18.8 \pm 0.3 \text{ fm} \\ a_{np}^N &= -23.75 \pm 0.09 \text{ fm}, \end{aligned} \tag{16}$$

in which the superscript N represents the "nuclear" effect obtained after the electromagnetic corrections have been made. The differences between these scattering lengths represent charge independence and charge symmetry breaking effects. There are very large percentage differences between these numbers which may seem surprising. But one must recall that that is the inverse of the scattering lengths that are related to the potentials. For two different potentials, V_1, V_2 the scattering lengths a_1, a_2 are related by

$$\frac{1}{a_1} - \frac{1}{a_2} = M \int_0^\infty dr\ u_1(V_1 - V_2)u_2 \tag{17}$$

where u_1 and u_2 are the wave functions, normalized so that their limit at large r is 1-r/a_i and u(0)=0. Evaluating Eq. (17) leads to the result[4],

$$\frac{\Delta a}{a} = (10 - 15)\frac{\Delta V}{V}, \tag{18}$$

where the variation between 10 and 15 arises from using different radial shapes for V(r). One defines Δa_{CD} to measure the charge independence breaking, with

$$\Delta a_{CD} \equiv \frac{1}{2}(a_{pp}^N + a_{nn}^N) - a_{np}^N = 5.7 \pm 0.3 \text{ fm}. \tag{19}$$

The charge dependence breaking is then about about 2.5% if one uses Eq. (18). The breaking of charge symmetry CSB is represented by the quantity

$$\Delta a_{CSB} \equiv a_{pp}^N - a_{nn}^N = 1.5 \pm 0.5 \text{ fm}. \tag{20}$$

Some computations[32,40,41] of Δa_{CD} are displayed in Table 1. The agreement with the experimental value of $\Delta a_{CD} = 5.7 \pm 0.5$ fm is very good. The errors allow some room for other effects, including those due to explicit quark effects. It is clear that the understanding of charge dependence has been rather good.

Table 1. Calculations of Δa_{CD} (fm)

Figure 4: ρ^0-ω exchange contributions (a) Short range, strong interaction effect; (b) Long range, electromagnetic effect

	Henley, Morrison [32] 1966	Ericson, Miller[40] 1983	Cheung, Machleidt [41] 1986
OPEP	3.5	3.5 ± 0.2	3.8 ± 0.2^a
TPEP (all)	0.90	0.88 ± 0.1	0.8 ± 0.1
Coupling Constants	b	0^c	
$\gamma\pi$		1.1 ± 0.4^d	1.1 ± 0.4^d
Total		5.5 ± 0.3	5.7 ± 0.5

a. This also includes the effects of $\pi\rho, \pi\omega$ and $\pi\sigma$ exchanges.
b. Henley and Morrison showed that one could choose charge dependent coupling constants to describe the remainder of Δa_{CD}, but these were unknown.
c. The effect of using charge dependent coupling constants tends to cancel if these are used consistently in OPEP and TPEP.
d. This is an average[40] of the results of Refs. [33] and [34].

Now consider the charge symmetry breaking mechanisms responsible for the non-zero value of Δa_{CSB}. The previously dominant one-pion exchange effect is absent here since only neutral pions are exchanged. Other mechanisms are needed, with the exchange of a mixed $\rho^0\omega$ meson a natural choice. This is shown in Figs. 4a and 4b. The electromagnetic contribution, Fig. 4b, is part of the long range, electromagnetic interaction as modified by the vector meson contribution to the form factors. The strong interaction term gives a nucleon-nucleon force of a medium range. This leads to a contribution to Δa_{CSB} of 1.4 fm, obtained by rescaling the Coon and Barrett[18] result by the ratio $1.1 \left(\frac{5160}{4652}\right)$. This accounts for the observed effect $\Delta a_{CSB} = 1.5 \pm 0.5$ fm, while other effects seem small[18].

This agreement with experiment may not be satisfactory. A significant extrapolation is involved since $< \rho^0 | H_{str} | \omega >$ is determined at $q^2 = m_\rho^2$, while in the NN force the relevant q^2 are spacelike, less than or equal to zero. Goldman, Henderson

Figure 5: Quark model of ρ^0-ω mixing.

Figure 6: Model of Krein, Thomas and Williams - q^2 variation of $< \rho^0 | H_{str} | \omega >$

and Thomas[42] investigated the possible q^2 dependence of $< \rho^0 | H_{str} | \omega >$ by evaluating the diagram of Fig. 5 using free quark propagators. They obtained a substantial q^2 dependence. The use of such a $< \rho^0 | H_{str} | \omega >$ obliterates the resulting charge symmetry breaking potential and its effects in nucleon-nucleon scattering[43]. Similar results for the mixing matrix element were also obtained in the work of Refs. [44]-[48]. Furthermore, O'Connel at al.[49] have argued that within a broad class of models the amplitude for ρ^0-ω mixing must vanish at the transition from timelike to spacelike four momentum. However, this result is obtained by assuming that "there is no explicit mass-mixing term in the bare Lagrangian." QCD has such a term and we therefore expect that any equivalent effective hadronic theory would contain such a term. Thus, this vanishing need not occur.

Our view is that the charge symmetry breaking effects of the d-u mass difference in vector exchanges must persist, with little variation in q^2, whether one works directly with quarks or one uses hadronic matrix elements to capture the quark effects. However, we examine the consequences of the idea that $< \rho^0 | H_{str} | \omega >$ does have a strong variation with q^2.

Consider the results of the "minimal" model of Krein, Thomas and Williams[45] which are displayed in Fig. 6. This work models confinement in terms of pole-less

Figure 7: Quark model of the ρ^0-γ^* transition

quark propagators. Here we emphasize Miller's argument[50] that models which obtain the q^2 dependence of $< \rho^0|H_{str}|\omega >$ from the diagram of Fig. 4 have an implicit prediction for the q^2 variation of the ρ-γ^* transition matrix element $e/f_\rho(q^2)$, see Fig. 7. Miller's evaluation of this using the minimal model of Ref. [45] is shown in Fig. 8. A significant variation is seen, with a gain of a factor of four in the magnitude of $e/f_\rho(q^2)$ as q^2 is increased from 0 to m_ρ^2. This is a noteworthy observation because $f_\rho(q^2)$ can be extracted from $e^+e^- \rightarrow \rho \rightarrow e^+e^-$ data at $q^2 = m_\rho^2$ and from the high energy $\gamma p \rightarrow \rho^0 p$ reaction at $q^2 = 0$. The results of many experiments are discussed in the beautiful review of Bauer, Spital, Yennie and Pipkin[51]. They summarize $f_\rho^2(q^2 = m_\rho^2)/4\pi = 2.11 \pm 0.06$ and $f_\rho^2(q^2 = 0)/4\pi = 2.18 \pm 0.22$, as obtained from experiments at the CEA, DESY, SLAC and Cornell. Real photon data at energies from 3 to 10 GeV are used in the analysis.

No variation of $f_\rho(q^2)$ with q^2 is seen in the data! This seems to be in strong disagreement with the consequences of the models of Refs. [42]-[48]. The survival of such models seems to depend on finding a new way to account for the $\gamma p \rightarrow \rho^0 p$ data as well as for data on many γ-nucleon and nuclear reactions.

Coon and Scadron[52] use tadpole dominance to argue that $\rho^0\omega$ exchange predicts an important charge symmetry breaking nucleon-nucleon potential. In Feynman diagrams, tadpoles are represented by external lines which account for SU(2) and SU(3) symmetry breaking effects when inserted into a meson or baryonic line. The $\Delta I = 1$ tadpole form contributes a term $H_{tad}^3 = c' H_3 = (m_u - m_d)(\bar{u}u - \bar{d}d)/2$ to the Hamiltonian. One can compute matrix elements of the operator $(\bar{u}u - \bar{d}d)$ using symmetry arguments. Then one can account for the SU(2) and SU(3) violations of hadrons covering a wide range of mass with only one mass-independent parameter. Thus, in this picture, the mixing matrix elements have no dependence on the four-momentum squared of the hadrons.

Thus it is still reasonable[50,52] to assume that $< \rho^0|H_{str}|\omega >$ has little dependence on q^2. Then charge symmetry breaking in the $^1\mathrm{S}_0$ channel is accounted for and there are many consequences, see Sects. 2.6, 2.7, 3.2 and 3.3.

A similar discussion regarding off-shell dependence can be carried out with respect to π^0-η mixing[53]. The presumed small value of the η-nucleon coupling constant seems to make this effect much less influential for nucleon-nucleon interactions than ρ^0-ω mixing. However, π^0-η mixing could be important in understanding charge symmetry breaking in pion production reactions; see Sect. 3.3. This involves higher energy than elastic scattering, so the π and the η are on or near the mass-shell and a possible off-shell variation is less significant. A new approach to $\pi - \eta$ mixing is discussed in

Figure 8: q^2 variation of $\frac{1}{f_\rho}$. The magnitude of f_ρ has been scaled to allow a comparison with the q^2 dependence of $< \rho^0 | H_{str} | \omega >$.

Ref. [54].

2.4 Classification of Charge Dependent Nucleon-Nucleon Forces

We have seen that some mechanisms contribute to Δa_{CD} and others to Δa_{CSB} and some to both. Moreover there are other observables involving spin-dependent symmetry breaking effects. It is therefore useful to characterize the charge dependence of nuclear forces according to their isospin dependence. The discussion of Henley and Miller[5] listed four classes.

Class (I): Forces which are isospin or charge independent. Such forces, V_I obey $[V_I, \vec{T}] = 0$ and thus have the isoscalar form

$$V_I = a + b\vec{\tau}(i) \cdot \vec{\tau}(j) \tag{21}$$

where a and b are reasonable isospin independent operators and i and j label two nucleons.

Class (II): Forces which maintain charge symmetry but break charge independence. These can be written in an isotensor form

$$V_{II} = c[\tau_3(i)\tau_3(j) - \frac{1}{3}\vec{\tau}(i) \cdot \vec{\tau}(j)]. \tag{22}$$

The Coulomb interaction leads to a Class II force as do the effects of the pion mass difference in the one pion exchange interaction and possible effects of charge dependent coupling constants.

Class (III): Forces which break both charge independence and charge symmetry, but which are symmetric under the interchange $i \leftrightarrow j$ in isospin space,

$$V_{III} = d[\tau_3(i) + \tau_3(j)]. \tag{23}$$

A class III force differentiates between nn and pp systems. However, it does not cause isospin mixing in the two-body system, since

$$[V_{III}, T^2] \propto [T_3, T^2] = 0. \tag{24}$$

This force vanishes in the np system. The effects of the exchange of a mixed $\rho^0 - \omega$ meson yield a significant class III force. The effects of the quark mass difference that appear in the one-gluon exchange interaction also contribute.

Class (IV): Class IV forces break charge symmetry and therefore charge dependence; they cause isospin mixing. These forces are of the form

$$V_{IV} = e[\vec{\sigma}(i) - \vec{\sigma}(j)] \cdot \vec{L}[\tau_3(i) - \tau_3(j)] + f[\vec{\sigma}(i) \times \vec{\sigma}(j)] \cdot \vec{L}[\vec{\tau}(i) \times \vec{\tau}(j)]_3, \tag{25}$$

where e and f are reasonable spin-independent operators. The e term receives contributions from γ, and $\rho\omega$ exchanges; while f is caused by the influence of the neutron-proton mass difference on π and ρ exchange. Charge dependence of the coupling constants gives no Class IV force.

Class IV forces vanish in the nn and pp systems, but cause spin-dependent isospin mixing effects in the np system. As a result the analyzing power of polarized neutrons scattered from unpolarized protons, $A_n(\theta_n)$, differs from the analysing power of polarized protons scattered from unpolarized neutrons, $A_p(\theta_p)$[55,56]. Measurements at TRIUMF[57] and the IUCF[58] compared scattering of polarized neutrons to scattering of unpolarized neutrons from an unpolarized, respectively a polarized proton target. Time reversal invariance relates the latter measurement to A_p. These analyzing powers pass through zero at one angle θ_0 for the energies of the TRIUMF and IUCF experiments. If θ_0 for polarized neutrons differs from θ_0 obtained for polarized protons, then $\Delta\theta \equiv \theta_0(n) - \theta_0(p) \neq 0$ and charge symmetry has been violated. The results of the two beautiful experiments are presented in terms of $\Delta A (= \frac{dA}{d\theta} \Delta\theta)$, and are shown in Fig. 9. The calculations[59] use the Bonn meson-exchange potential so that all of the parameters governing the strong interaction are pre-determined. (Other calculations are discussed in Ref. [6].) The agreement between theory and experiment is very good. A pion exchange effect arising from the presence of the n-p mass difference in the evaluation of the vertex function dominates the 477 MeV measurement[60]. The ρ^0-ω mixing term has a significant but non-dominating influence at 183 MeV.

A new TRIUMF experiment, performed at 350 MeV, is discussed in Sect. 3.2.

2.5 The ^{3}He-^{3}H Binding Energy Difference

Figure 9: Measured values of $\Delta A \equiv A_n - A_p$ for np elastic scattering at 183 MeV (IUCF) and 477 MeV (TRIUMF). The horizontal lines represent theoretical predictions of Ref. [59].

The ground state binding energy difference $B(^3\mathrm{H}) - B(^3\mathrm{He}) = 764$ keV is a measure of the breaking of charge symmetry[62]. The proton rich ^{3}He nucleus is less deeply bound because of the repulsive influence of the Coulomb interaction and other electromagnetic effects. Such effects must be removed to determine the strong interaction charge symmetry breaking. The three body system is the best for such evaluations because the most important electromagnetic terms can be evaluated in a model independent way using measured electromagnetic form factors[61]. Coon and Barrett[18] used recent data to obtain

$$\Delta B(em) = 693 \pm 19 \pm 5 \text{ keV}, \tag{26}$$

where the first uncertainty is due to the determination of the form factors, and the second to the small model dependence of some relativistic effects. Similar values of $\Delta B(em)$ were obtained in Ref. [63]. The difference between 764 and 693 is about 71 keV, to be accounted for by charge symmetry breaking of the strong interaction. The use of a $\rho^0\omega$ exchange potential which reproduces Δa_{CSB} yields about 90 ± 14 keV in good agreement with the experimental difference. The errors allow some room for other small effects such as $\pi\eta$ or $\pi\gamma$ exchanges. A discussion of the precise value of the Coulomb energy difference is given in Ref. [64].

2.6 Nolen–Schiffer Anomaly and Other Nuclear Structure Effects

The pattern of charge symmetry breaking seen for A=3 also occurs for the mirror nuclei $(N, Z) = (Z, Z + 1)$ and $(Z + 1, Z)$. Charge symmetry predicts an equality between the binding energies, but differences are observed. It was first thought that electromagnetic, mainly Coulomb, effects could account for all of the observed binding energy differences. Evaluating the consequences of the electromagnetic effects is hindered by the need to account for various correlation effects in the nuclear wavefunction. Nolen and Schiffer[3] made an extensive analysis, finding that the electromagnetic effects were not sufficient. There was a residual effect due to charge symmetry breaking of the strong interaction: the neutron rich nuclei were seen to be more deeply bound (by about 7%) than the proton rich nuclei. Including additional detailed nuclear structure effects reduced the number, but only to a rather substantial 5%. See the reviews [6],[65] and Ref. [66]. Negele also suggested[66] that the charge symmetry violation in the two-nucleon force could be responsible for the missing 5% binding energy difference.

Since the early seventies many authors have tried to better understand the anomalous 5%, see the review [6]. This was not easy because the charge symmetry breaking of the nucleon-nucleon force was very uncertain. An early $\pi^- d \to nn\gamma$ experiment[67] obtained a scattering length with an error of 1.3 fm. This was large enough to say that the nn force was either significantly more attractive or significantly more repulsive than the pp force. This was remedied by the PSI measurements[68,69] of the neutron-neutron scattering lengths in the $\pi^- d \to nn\gamma$ reaction which indicated significantly more attraction for the nn force. Additionally, the TRIUMF and IUCF

np scattering experiments increased the awareness of the fundamental mechanism for charge symmetry breaking in the nucleon-nucleon interaction.

Thus the climate was right for attacking the Nolen-Schiffer anomaly with a meson exchange theory of the charge symmetry breaking nucleon-nucleon potential when Blunden and Iqbal[70] took up the challenge. As shown in Table 2, a good account was obtained.

Table 2. Blunden and Iqbal[70] treatment of the Nolen–Schiffer anomaly. The first column identifies the nucleus and the single particle state. The next two present the value of the non-electromagnetic contribution to the binding energy difference, as evaluated in Ref. [71] using the density matrix expansion DME or Skyrme II interaction SKII. The next two columns represent computed binding energy differences, showing the total contributions and the individual effect of the ρ^0-ω term, rescaled to use the value of $< \rho^0|H_{str}|\omega >= -5200$ MeV^2.

A	orbit	Required CSB (keV)		Calc. CSB (keV)	
		DME	SkII	total	$\rho^0 - \omega$
15	$p_{3/2}^{-1}$	250	190	210	182
	$p_{1/2}^{-1}$	380	290	283	227
17	$d_{5/2}$	300	190	144	131
	$1s_{1/2}$	320	210	254	218
	$d_{3/2}$	370	270	246	192
39	$1s_{1/2}^{-1}$	370	270	337	290
	$d_{3/2}^{-1}$	540	430	352	281
41	$f_{7/2}$	440	350	193	175
	$1p_{3/2}$	380	340	295	258
	$1p_{1/2}$	410	330	336	282

The total charge symmetry breaking contribution to the binding energy difference is in good agreement with the amount required, which depends slightly on the nuclear wave function. Thus charge symmetry breaking effects in the strong interaction do account for the missing binding energy difference, with the bulk accounted for by the influence of ρ^0-ω mixing. Similar results have been obtained in Refs. [72] and [73]. Furthermore, Krein, Menezes and Nielsen[74] included ρ^0-ω mixing in the framework of the relativistic σ, ω (Walecka) model of nuclear matter. Those authors find a charge symmetry breaking effect of about the right sign and magnitude, and an explanation of the same kind as that of Refs. [70]-[73]. Krein and collaborators[75] have recently extended this work to the case of finite nuclei, with the same conclusion. The Blunden-Iqbal explanation was criticized in Ref. [76] for using a larger value of the ρ–nucleon coupling constant than that predicted by vector dominance. However, the value is consistent with that of the Bonn potential and therefore seems well-constrained.

So far we have discussed explanations of the Nolen-Schiffer anomaly in terms of vector mesons. But there is an entire class of explanations[77–83,76] which examine the scalar effects of the nuclear medium which modify the neutron-proton mass difference, M_n-M_p. Reducing M_n-M_p corresponds to increasing the neutron attraction, which is needed to explain the Nolen–Schiffer anomaly.

Several investigations were stimulated by the work of Krein and Henley[77] who included effects of the nuclear medium in the Nambu–Jona–Lasinio model[10] for chiral symmetry breaking. Including a non-zero nuclear density leads to a Pauli principle suppression of the loop diagrams which generate the constituent mass. This decreases the value of the quark condensates leading to a partial restoration of chiral symmetry in nuclei. The result, as computed in a constituent quark model, is that the neutron-proton mass difference M_n-M_p decreases as the nuclear density increases. This is the kind of effect needed to account for the Nolen-Schiffer anomaly. However, when the constituent quark model of a nucleon is replaced by a chiral soliton model[84,85] or by a chiral model with nucleon and meson degrees of freedom[86], M_n-M_p increases or remains the same as the density is increased. These three papers contradict the basic Krein and Henley result.

However, the Krein and Henley mechanism can be evaluated using QCD sum rules[78−82,76]. The aim of such treatments[78] is to express the neutron-proton mass difference to the vacuum parameters $m_d - m_u$ and $\gamma =< \bar{d}d > / < \bar{u}u > -1$, in a manner which avoids using an explicit model for the nucleon. The use of QCD sum rules yields results that do tend to explain the Nolen–Schiffer anomaly. This agreement may be illusory due to an important nuclear effect, first utilized by Williams and Thomas[87]. The nuclear Coulomb repulsion pushes a valence proton away from the nuclear center. Thus a valence proton sees a lower density than a valence neutron, i.e. $\rho_p < \rho_n$. This is a substantial effect; $\rho_n = 0.0667 fm^{-3}, \rho_p = 0.0594 fm^{-3}$ for the valence nucleon of ^{41}Ca-^{41}Sc[87]. Taking this effect into account, Fiolhais et al.[84] find a very small attraction for the neutron even though the neutron-proton mass difference increases with density (for $\rho_n = \rho_p = \rho$). Such effects should be included in future QCD sum rule calculations. Note also that a general criticism of such calculations is the sensitivity to previously undetermined condensates, see e.g. Ref. [88].

The work of Saito and Thomas[83] studies the Nolen–Schiffer anomaly using their quark-meson coupling model. In this mean-field model of nuclear matter non-overlapping nucleon bags are bound by the self-consistent exchange of σ, ω and ρ mesons. The effects of self-consistent exchange of σ mesons combined with the quark mass difference leads to different bag energies for up and down quarks. A qualitative, but not precise, explanation of the anomaly is achieved. This work includes the nuclear structure effect of Ref. [87].

Thus there are two main mechanisms to explain the Nolen–Schiffer anomaly. The vector effects of ρ^0-ω mixing; and, the scalar effects of the medium modifications (Pauli principle) of the nucleon mass. The first mechanism is closely related to nucleon-nucleon scattering, Sect. 2.3, and is very traditional. It is easy to relate this effect to the A=3 system for which the nuclear wave function is mainly irrelevant. The second mechanism is newer, more speculative, harder to evaluate but has many implications. It is related to explanations of the EMC effect. Most likely, both mechanisms are present. Our view coincides with that of Blunden and Iqbal, some 70% or more of the anomaly is explained by ρ^0-ω mixing. This leaves plenty of room

for substantial scalar effects of the nuclear medium. In any case, the Nolen Schiffer anomaly is no longer a puzzle. The quark mass difference, whether by vector or scalar effects, is responsible.

There are other puzzles concerning the energy differences between heavier nuclei (^{48}Ca, ^{90}Zr, ^{208}Pb) and their isobaric analog states. See e.g. the review[89]. The energy differences between these nuclei and their isobaric analog states are mainly due to Coulomb effects. However, there is a remainder to be attributed to charge dependent forces. Naively, one would think that this remainder should increase with the neutron excess. This was found not be to be the case[90]. For example, in ^{48}Ca, the sign of the remainder was less than for ^{41}Ca. This puzzle was resolved by Suzuki, Sagawa and Van Giai[91] who showed that it is necessary to use both charge symmetry and charge independence breaking forces consistent with the NN data to compute the relevant binding energy differences. The A dependence seems now to be well understood. A remaining problem is that the purely theoretical potentials do not give quantitative agreement. The theoretical potentials used in Ref. [91] reproduce only about 70% of Δa_{CD}, as the $\gamma\pi$ term was not included.

Ormand and Brown have also included charge dependent nuclear forces as input to their shell model calculations[92–94]. An isospin non–conserving interaction was used to understand the spectroscopic amplitudes for the decay of T=3/2 states in A=4n+1 nuclei (21$\leq$ A $\leq$ 37) by proton and neutron emission to the T=0 ground states[93] also to include correction to the Fermi matrix element in β decays[92]. The charge dependent interactions used are phenomenological, but are in general agreement with the results expected from nucleon-nucleon scattering data. The proton-neutron interaction is about 2% more attractive than the average of the proton-proton and neutron-neutron interactions. Furthermore, including a charge symmetry breaking interaction helps to improve the agreement between theory and experiment. It would be of interest to use charge dependent strong interactions as predicted by meson exchange theory, especially for the contributions of the $\pi^{\pm}$-π^0 mass difference and ρ^0-ω exchange.

2.7 Charge Symmetry Breaking in Hypernuclei

Hypernuclear binding energy differences allow tests of charge symmetry of the ΛN interaction. The main source of information is the mirror pair ${}^4_\Lambda H$, ${}^4_\Lambda He$; see the reviews[22,95]. Not much data is available for other nuclei[6]. The difference between the Λ separation energies of the ground state[96]

$$B_\Lambda({}^4_\Lambda He) \equiv B({}^4_\Lambda He) - B({}^3He) = 2.39 \pm 0.03 MeV \tag{27}$$

and

$$B_\Lambda({}^4_\Lambda H) \equiv B({}^4_\Lambda H) - B({}^3H) = 2.04 \pm 0.04 MeV \tag{28}$$

provided evidence for a charge symmetry breaking component of the Λ- N interaction[20]. These values must be corrected for Coulomb and other electromagnetic effects to determine the strong interaction charge symmetry breaking. A complete four-body

calculation is required to do this, a folding model of the Λ nucleus interaction is not sufficient[97].

Extensive work on the ΛN interaction, including the effects of charge symmetry breaking, was done by the Nijmegen group[98] which takes the most important source to be Λ-Σ^0 mixing (Sect. 2.2). This allows a π^0 to couple to the physical Λ, so the charge symmetry breaking potential has the range of one pion exchange and consists of a spin-spin and tensor interaction. The Σ is only 80 MeV heavier than the Λ, so coupling to the ΣN channel is important and the mass differences between the different Σ charge states also contribute. Comprehensive fits to data for Σ-p reactions led this group to predict the charge symmetry breaking of the ΛN interaction, even though there are no data for that channel. Gibson and Lehman[99] made model calculations using separable potentials fitted to the scattering length and effective ranges of the Nijmegen model D potential. This was sufficient to account for the observed charge symmetry breaking of the ground states. Gibson[100] emphasized the importance of the Σ mass differences in computing the level orderings of the ^{4}He ground and excited states. However, it is reasonable to assume that the effects of Λ-Σ^0 mixing and ρ^0-ω mixing are far more important for the ΛN charge symmetry breaking interaction.

Bodmer and Usmani[101] considered also the charge symmetry breaking of the first excited states, using extensive variational calculations. The Λ separation energies of the lowest 1^+ excited states are[102]

$$B_\Lambda(^4_\Lambda He^*) \equiv B(^4_\Lambda He^*) - B(^3He) = 1.24 \pm 0.06 MeV \tag{29}$$

and

$$B_\Lambda(^4_\Lambda H^*) \equiv B(^4_\Lambda H^*) - B(^3H) = 1.00 \pm 0.06 \ MeV. \tag{30}$$

They determined the Coulomb contributions to improved accuracy; the differences of B_Λ for the ground and excited states were found to be 0.40±0.06 and 0.27± 0.06 MeV. These results could be described by a charge symmetry breaking potential which effectively is independent of spin, in contrast with the one-pion-exchange effect. Thus, the potentials of Ref. [98] do not describe the charge symmetry breaking when one considers both the ground and excited states. This conclusion relies upon the ability of variational methods to handle the four body problem. Bodmer and Usmani used a very detailed correlated wave function. They tested their procedure by applying it to ^{3}He, obtaining excellent agreement between their variational wave function and the exact Green function results. Thus the procedure seems adequate. It would still be desirable to confirm the Bodmer-Usmani results with an independent calculation.

Thus the need to understand why the ΛN charge symmetry breaking interaction is approximately independent of spin is an unsolved problem, so we make a suggestion. The effects of exchange of a mixed ρ^0-ω meson have been ignored since the very early work of Downs[103] who argued that cancellations take place when the effects of mixing between the ρ, ω and ϕ mesons are all included. But this is based on

early values of meson-baryon coupling constants, and on radial potentials with a Yukawa form instead of the exponential form obtained when two meson propagators are involved. It is certainly time to take a new look at the role of meson mixing in the ΛN interaction. In particular, the exchange of a mixed ρ^0-ω meson leads to a substantial central interaction.

3. New experimental information

Effects of charge independence and charge symmetry breaking have been sought with many different projectiles and targets. These experiments are intrinsically challenging because of the small nature in most instances of the effects being sought. Nevertheless, substantial progress has been achieved.

3.1 Low-Energy Nucleon-Nucleon Scattering

The earliest evidence for the breaking of charge independence in nucleon-nucleon scattering was the inequality of the N-N scattering lengths. In particular, charge independence breaking occurs in the difference $\frac{1}{2}(a_{nn}^N + a_{pp}^N) - a_{np}^N = (5.7 \pm 0.3)$ fm, where a_{nn}^N, a_{pp}^N, and a_{np}^N are given in Table 3. This difference of 5.7 ± 0.3 fm can be explained as resulting predominantly from the mass difference between the neutral and charged pions; see Sect. 2.3. The quantities a_{pp}^N, a_{nn}^N and a_{np}^N are pp, nn and np scattering lengths, corrected for Coulomb effects and vacuum polarization.

Table 3
Low energy nucleon-nucleon scattering observables

	$nn^{67,68,69}$	nn^{N6}	np^{N104}	pp^{31}	pp^{N6}
a(fm)	-18.45±0.32	-18.8±0.3	-23.748±0.009	-7.8063±0.0026	-17.3±0.4
r(fm)	2.80±0.11	2.75±0.11	2.75±0.05	2.794±0.0014	2.85±0.04

Charge symmetry breaking is a smaller effect than charge independence and therefore is more subtle. Its influence can be seen through a difference of the pp and nn scattering lengths, but obtaining a precise value has been difficult. The ability to remove Coulomb effects from the experimentally observed pp scattering length depends on knowing the short range part of the nucleon-nucleon interaction[105]. Nowadays, quark models can be used to limit the uncertainties in the short-distance strong interaction; see the review[6] and Ref. [106]. Progress is possible.

It is the lack of a free neutron target that causes the most difficulties in observing neutron-neutron scattering and its difference from proton-proton scattering. Proposals to scatter neutrons from neutrons have appeared from time to time. But no real experiment has ever been reported in the scientific literature. The most reliable

determinations of a_{nn} as well as the effective range r_{nn} occur in three-body reaction studies with only two strongly interacting particles (the two neutrons) in the final state. Consequently a_{nn} and r_{nn} are mainly deduced in studies of the reaction $\pi^- d \rightarrow \gamma nn$. The result is a small inequality of the nn and pp scattering lengths, with the nn scattering length ($a^N_{nn} = -18.8 \pm 0.3$ fm[6]) slightly more negative than the pp scattering length ($a^N_{pp} = -17.3 \pm 0.4$ fm[6]), giving a difference of $a^N_{pp} - a^N_{nn} = -1.5 \pm 0.5$ fm. A 1 fm difference between the scattering lengths corresponds to only about a part in 200 difference between the potentials. It is necessary to find other manifestations of charge symmetry breaking to establish its existence.

We next discuss the use of the deuteron breakup reactions nd→nnp and pd→ppn in determining nucleon-nucleon scattering parameters. The three nucleon final states must be analyzed with Faddeev calculations in order to extract the low-energy nucleon-nucleon scattering parameters. The treatment of Coulomb effects in Faddeev calculations is extremely complicated and cannot be done without approximations; see eg. the recent review[39]. For a recent report on including the Coulomb interaction in Nd breakup calculations see ref. [107]. A precise direct comparison between nn observables (from nd) and pp observables (from pd) is not yet possible.

It is more reasonable to attempt to determine the nn scattering parameters from the nd breakup reaction. However, even though a great deal of effort has gone into understanding the three nucleon final state reactions in a quantitative way[39,108], we continue to doubt their use in obtaining precise values of of a_{nn} and r_{nn}. A recent example of such a determination is the measurement of $^2H(n, nnp)$ at 10.3 and 13.0 MeV[109], which contains several advances. Comparisons between experiment and modern theory in various regions of phase space show good agreement. Furthermore, these authors test their method by trying to extract the known value of a_{np}. Including a charge dependent improvement to the Paris potential clearly improves the agreement between theory and experiment. Thus they clearly demonstrate that their method can certainly observe a 5-7 fm effect in the scattering length. However, the level of precision required to learn about charge symmetry breaking is about 0.5 fm or better. We doubt this precision is possible now. Even in the kinematic region where the np final state interaction dominates, the agreement is not excellent; and there are significant disagreements between theory and experiment in other regions of phase space. There are other obstacles. It has been reported that the extraction of a_{nn} from kinematically complete nd breakup data in state-of-the-art analyses is sensitive to the choice of the nucleon-nucleon potential[110]. Even if one starts with realistic nucleon-nucleon interactions, it is often convenient to make approximations, such as using a single separable potential, to incorporate these interactions in the Faddeev formalism. Furthermore, the extracted value of a_{nn} is sensitive to whether or not the effects of three body forces are included in the analysis[39]. For all these reasons, we question the present ability to determine the precise value of a_{nn} from the nn final state interaction region in the nd break-up reaction.

A new experimental effort to measure the low-energy nn scattering parameters is

underway at TRIUMF[111]. The experiment is a three-fold coincidence measurement of the $\pi^- d \rightarrow \gamma nn$ reaction with stopped pions. It is anticipated that the nn scattering length a_{nn} and effective range parameter r_{nn} can be determined to an accuracy comparable to or better than obtained previously in the PSI measurements[68,69].

3.2 np Scattering

Charge symmetry leads to the complete separation of the isoscalar and isovector components of the np interaction. This in turn leads to the equality of the differential cross sections for polarized neutrons scattering from unpolarized protons and vice versa. As a result $A_n(\theta) \equiv A_p(\theta)$ where A denotes the analyzing power and where the subscript represents the polarized nucleon. A nonvanishing asymmetry difference is directly proportional to the isotopic spin singlet-triplet, spin singlet-triplet mixing amplitude and therefore direct evidence of a charge-asymmetric interaction, antisymmetric under the interchange of nucleons 1 and 2 in isotopic spin space; see Sect. 2.4.

The scattering matrix for np elastic scattering can be expressed in terms of the formalism of LaFrance and Winternitz[112] as

$$M(\vec{k}_f, \vec{k}_i) = \frac{1}{2}\{(a+b) + (a-b)(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) + (c+d)(\vec{\sigma}_1 \cdot \hat{m})(\vec{\sigma}_2 \cdot \hat{m}) \\ +(c-d)(\vec{\sigma}_1 \cdot \hat{\ell})(\vec{\sigma}_2 \cdot \hat{\ell}) + \epsilon(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{n} + f(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{n}\}. \qquad (31)$$

Here $\hat{\ell}$, $\hat{m}$ and $\hat{n}$ are unit vectors given as

$$\hat{\ell} = \frac{\vec{k}_i + \vec{k}_f}{|\vec{k}_i + \vec{k}_f|};\ \hat{m} = \frac{\vec{k}_f - \vec{k}_i}{|\vec{k}_i + \vec{k}_i|};\ \hat{n} = \frac{\vec{k}_i \times \vec{k}_f}{|\vec{k}_i \times \vec{k}_f|}; \qquad (32)$$

with $\vec{k}_i$ and $\vec{k}_f$ the initial and final state center-of-mass nucleon momenta. The amplitudes a, b, c, d, e and f are functions of center-of-mass energy E and scattering angle θ. Written explicitly, the difference in the analyzing powers

$$\Delta A(\theta) \equiv A_n(\theta) - A_p(\theta) = \frac{2}{\sigma_0}\mathcal{R}e(b^* f), \qquad (33)$$

is proportional to f. The quantity σ_0 is the differential cross section for the scattering of unpolarized neutrons from unpolarized protons.

Experimental considerations show that the next least difficult quantity to measure is the difference in the spin-correlation parameters $C_{xz}(\theta)$ and $C_{zx}(\theta)$. The correlation parameter C_{xz} requires the projectile spin to be polarized transverse to the beam direction in the scattering plane and the target spin polarized along the incident beam direction, while for C_{zx} the reverse holds. Charge symmetry leads to the equality of $C_{xz}(\theta)$ and $C_{zx}(\theta)$, but if charge symmetry is broken then one would be able to measure a difference

$$\Delta C(\theta) \equiv C_{xz}(\theta) - C_{zx}(\theta) = \frac{2}{\sigma_0} Im(c^* f). \qquad (34)$$

Due to the intrinsic difficulties of excluding extraneous polarization components in both the incident beam and the scattering target, measurements of $\Delta C \equiv C_{xz} - C_{zx}$ have not yet been attempted. Other observables are defined by LaFrance and Winternitz[112].

The first measurement of charge symmetry breaking in np elastic scattering was performed at TRIUMF[57]. The measurement of $\Delta A \equiv A_n - A_p$, at the zero-crossing angle of the average analyzing power, at an incident neutron energy of 477 MeV, yielded $\Delta A = (47 \pm 22 \pm 8)\times 10^{-4}$, a little over two standard deviations effect. More recently the results of a similar experiment at a neutron energy of 183 MeV performed at IUCF have been reported[58]. The measured value of $\Delta A \equiv A_n - A_p$, averaged over the angular range $82.2^\circ \leq \theta_{cm} \leq 116.1^\circ$ over which $< A(\theta) >$ averages to zero, is $(33.1 \pm 5.9 \pm 4.3) \times 10^{-4}$, where again the first error represents mainly the statistical uncertainty and the second error the systematic uncertainty. The latter result differs from zero by 4.5 standard deviations (see Fig. 9). It differs from the value expected from the electromagnetic spin-orbit interaction by 3.4 standard deviations. This difference represents the strongest experimental evidence to date of charge symmetry breaking in the nuclear interaction.

There are difficulties in extracting an angular distribution of $\Delta A(\theta)$. This follows directly from the expression for the difference in the asymmetries for beam and target polarized, respectively, or

$$\epsilon_b(\theta) - \epsilon_t(\theta) = \Delta A(\theta)(P_b + P_t)/2 + < A(\theta) > (P_b - P_t), \tag{35}$$

pointing to the need for calibration of the beam and target polarizations (P_b and P_t) with an accuracy unattainable at present. In the analysis of the IUCF experiment this difficulty was overcome by adjusting the ratio of (P_b/P_t) until the error-weighted rms value of $\Delta A(\theta)$ over the angular range of the experiment reached minimal variance. Following this procedure a twelve point angular distribution was obtained, see Fig. 10. The procedure does not work at 477 MeV where $\Delta A(\theta)$ and $< A(\theta) >$ have zero-crossing angles in close proximity and consequently the angular dependencies are no longer orthogonal. If the theoretical calculations were precise in their predictions of the zero-crossing angle of $\Delta A(\theta)$ one could in principle also determine $\Delta P = P_b - P_t$ and consequently the angular distribution of $\Delta A(\theta)$ would follow.

In general, the measured analyzing power differences of the IUCF and TRIUMF experiments are well reproduced by theoretical predictions based on meson exchange potential models, which indirectly incorporate quark level effects. The calculations include contributions from one photon exchange (the magnetic moment of the neutron interacting with the current of the proton), from the neutron-proton mass difference affecting charged one π, ρ and ω exchange, and from the more interesting isospin mixing ρ^0-ω meson exchange. Some other smaller effects (like two $\pi-$exchanges not included in $\rho-$exchange) have also been evaluated[113]. The effects of $\pi\gamma$ exchanges have not yet been calculated for the two experiments under discussion. The theoretical results indicated by the solid and dashed lines in Fig. 9 are based on a momentum

space version of the Bonn nucleon-nucleon potential[59]. Note that the first two contributions mentioned suffice to give a theoretical prediction in agreement with the TRIUMF result. This is because at 477 MeV the effect arising from ρ^0-ω mixing crosses zero close to the zero-crossing angle of $< A(\theta) >$. Reproducing the IUCF result at 183 MeV with present calculations requires inclusion of the ρ^0-ω meson mixing contribution, an approximately two standard deviation effect.

Figure 10: Comparison of the measured $\Delta A(\theta)$ angular distribution at 183 MeV [IUCF] with calculations based on Ref. [59] and Ref. [114], which display different distorting potentials and different ρNN and ωNN coupling constants. Experimental data and theoretical curves have been subjected to a $\Delta A(\theta)$ variance minimization procedure. Total χ^2 values for each curve include statistical errors only (see [58]).

Figure 10 shows the calculations of Holzenkamp, Holinde and Thomas (HHT)[59] and of Beyer and Williams (BW)[114]. The differences reflect different ρNN and ωNN coupling constants. HHT use larger coupling constants, as determined by the the requirement that their one boson exchange potential model reproduce the charge symmetric data. Thus the better agreement with the data provided by calculations employing the stronger coupling constants is due to internal consistency among the ingredients of the HHT calculations. The charge symmetry breaking effects are evaluated using the same coupling constants that determine the charge-symmetric interaction. A calculation, with a similar consistency, has recently been made by Iqbal and Niskanen[115]. However, there is controversy regarding the role of ρ^0-ω mixing, recall Sect. 2.3. The theoretical predictions of Iqbal and Niskanen include contributions from one photon exchange, the np mass difference affecting charged π and ρ exchange, ρ^0-ω mixing, and two π exchanges not included in ρ exchange. The np scattering wave function was derived using the np phases from a charge independent phase shift analysis[116]. The effects of inelasticity amount to about 10% at 800 MeV but are vanishing small below[117].

A new measurement at 350 MeV has been made at TRIUMF (E369) (Ref. [118]), with data taking completed in the spring of 1993, to delineate the various contributions to charge symmetry breaking. This experiment is very similar to the earlier TRIUMF measurement at 477 MeV[57]. The 350 MeV neutron beam was produced using the (p, n) reaction on deuterium. The proton beam had an intensity of about $2\mu A$ and a polarization of about 0.70 and was incident on a 0.21 m long LD_2 target. The energy, the polarization, the position and direction of the proton beam were monitored throughout the experiment and controlled (in the case of position and direction) using a feedback system coupling two sets of split-plate secondary electron emission monitors (which determined the median of the intensity distribution) with steering magnets upstream in the beam transport line. At the two sets of split-plate secondary emission monitors the beam position was kept fixed with a standard deviation of ≤ 0.05 mm in both x and y intensity profiles. The beam energy monitor, based on range determinations, allowed the beam energy to be kept constant with a standard deviation of less than 30 keV (through minute changes in rf of the cyclotron and stripper foil position). The polarization was transferred from the proton to the neutron by making use of the large sideways to sideways polarization transfer coefficient r_t (-0.88 at 364 MeV). Required rotations of the polarization directions were obtained by a solenoid magnet (for the proton polarization direction) and a combination of two dipole magnets (for the neutron polarization direction). The 9° neutron beam passed a 3.3 m long, tapered steel collimator before impinging on a frozen spin type polarized proton target (containing butanol beads) positioned at 12.85 m from the center of the LD_2 target. Typical polarizations were 0.80 or higher. Scattered neutrons were detected in the angle range 24.0° to 42.4° in large area scintillation counters, while the recoil protons were observed in scintillation counter/wire chamber telescopes nominally centered at 53°. The detection apparatus had reflection symmetry about the neutron beam axis to increase the event rate and to allow with reversals of the beam and target polarization directions certain systematic errors to

be cancelled (a three dimensional picture of the detector setup is shown in Fig. 11). At the zero-crossing angle all systematic errors, except those due to background corrections, are eliminated to second order in an expansion, in the error contributions. Further experimental details can be found in [119].

Figure 11: Three dimensional view of the detection apparatus of the TRIUMF 350 MeV experiment measuring CSB in np elastic scattering.

To select elastically scattered np events, proton and neutron tracks were reconstructed and their energies were calculated from time–of–flight. Four kinematic variables, opening angle, coplanarity angle, kinetic energy sum and horizontal momentum balance, were formed and momentum dependent chi–square cuts were applied. Scattering asymmetries were calculated for the selected events, which included a small contribution of quasi–elastic (n, np) background events.

Experimental parameters were studied to understand the source of systematic errors. These parameters include beam energy, proton and neutron polarizations, split–plate secondary electron emission monitor asymmetries, neutron profile parameters and frozen spin target parameters. Corrections were made for the contribution of quasi–elastic background and for the average neutron beam energy difference due to the energy and polarization correlation of the neutron beam production reaction $D(\vec{p}, n)2p$. The frozen spin target with the the butanol beads replaced by carbon

beads was used to study the background contribution. It was determined that 2.5% of the selected events, with $\chi^2 \leq 6$ cuts in the four kinematical variables, were from background. The opening angle distributions of the carbon target data were normalized to those of the butanol target data by matching the tails of the distributions. Neutron beam energy and the energy dependence of the effective spin transfer coefficient were studied with a Monte Carlo simulation. The difference of effective average neutron beam energy of polarized and unpolarized beam was calculated and a correction was obtained.

A preliminary result for the difference of the zero–crossing angles is $\Delta\theta_{cm} = 0.48° \pm 0.08°(stat.) \pm 0.08°(syst.)$ based on fits of the asymmetry curves over the angle range $55.8° \leq \theta_{cm} \leq 85.4°$. With $dA/d\theta_{cm} = (-1.35 \pm 0.05) \times 10^{-2}\text{deg}^{-1}$, as determined from the measured asymmetries with the polarized target, the value of $\Delta A \equiv A_n - A_p$, where subscripts denote polarized nucleons, is $[65 \pm 11(stat.) \pm 11(syst.)] \times 10^{-4}$. More extensive data analysis is in progress. It is expected that with all data analyzed a statistical accuracy of about $\pm 0.04°$ in zero–crossing angle difference or 6×10^{-4} in ΔA as well as a more definite systematic error will be obtained[120].

3.3 Pion Production Experiments

a) $np \to d\pi^0$

Another experiment that tests the effects of class IV interactions is the measurement of the forward-backward asymmetry in the reaction $np \to d\pi^0$. In the absence of such interactions isospin is conserved and consequently the angular distribution is symmetric about 90° in the center-of-mass. A nonvanishing forward-backward asymmetry difference in the deuteron angular distribution

$$A_{fb} \equiv \frac{\sigma(\theta) - \sigma(\pi - \theta)}{\sigma(\theta) + \sigma(\pi - \theta)} \tag{36}$$

is direct evidence of a charge-asymmetry in the pion production interaction, which is anti–symmetric under the interchange of nucleons 1 and 2 in isotopic spin space.

The first calculations of A_{fb} by Cheung, Henley and Miller[55] show an energy dependence of A_{fb} that suggests a large negative value below 300 MeV. Recent calculations[121] give an angle integrated value of approximately -50 $\times$ 10^{-4} for A_{fb} near 280 MeV with $\pi^0 - \eta$ and $\pi^0 - \eta'$ mixing contributing almost an order of magnitude more than one photon exchange, the neutron-proton mass difference affecting charged one π- and ρ-exchange, and ρ^0-ω mixing. These contributions are strongly dependent on the meson mixing matrix elements and on the ηNN coupling constant. The recent studies of van Kolck[13] display the importance of charge symmetry breaking in π^0-nucleon scattering. This is because the charge symmetric scattering length a_0 is proportional to $m_d + m_u$, which would vanish in the limit of complete chiral symmetry. This allows the usually small charge symmetry breaking correction, proportional to $m_d - m_u$, to be comparatively large. The π^0-nucleon scattering influences

pion production through its contribution to the rescattering matrix element, but this effect has not yet been evaluated.

While A_{fb} has been measured for a range of energies, the large uncertainties of these measurements make them rather inconclusive[122–125]. A new measurement of A_{fb} at 281 MeV is in a preparatory stage at TRIUMF[126]. Using a broad range magnetic spectrometer set at zero degrees, the full angular distribution of the recoil deuterons will be measured in a single momentum setting, eliminating many systematic uncertainties. Remaining systematic uncertainties will be suppressed by measuring the response of deuterons with the same momentum and trajectory from $pp \to d\pi^+$, which must be symmetric about 90° in the centre-of-mass. The group's intention is to measure A_{fb} with a precision of approximately $\pm 7 \times 10^{-4}$.

Charge symmetry also imposes constraints on the vector and tensor polarizations of the deuteron if the reaction proceeds with unpolarized neutrons incident on an unpolarized proton target. It is to be noted that the vector polarization P_y and the tensor polarization component P_{xz} are odd functions in θ, while the tensor polarization components P_{xx}, P_{yy}, and P_{zz} are even functions in θ. Obtaining quantitative information about deviations from these symmetry relations will certainly be much more difficult than measuring the forward–backward asymmetry in the differential cross section angular distribution.

b) $dd \to ^4$ He π^0

In self–conjugate systems (which are characterized by $T_3 = 0$) a charge–symmetric Hamiltonian cannot connect states which differ in isospin by one unit. Consequently the reaction $dd \to {}^4\mathrm{He}\pi^0$ is forbidden if charge symmetry holds, so observing a non-zero differential cross section proves that charge symmetry is broken. The forward angle center-of-mass differential cross section at an incident energy of 600 MeV was estimated to be 0.2 pb/sr[127] mainly from a mechanism in which π^0-η and π^0-η' mixing is enhanced by the resonant (3,3) pion-nucleon interaction. Coon and Preedom[128] deduced a center of mass differential cross section for $dd \to ^4$He π^0 at 1.95 GeV of 0.12 $\pm$ 0.05 pb/sr. Their mechanism is the dd$\to ^4$Heη reaction followed by external $\eta - \pi^0$ mixing. Their value for the $dd \to ^4$Heπ^0 cross section was obtained using a measured value for the reaction $dd \to {}^4\mathrm{He}\eta$ at 1.95 GeV and at $\theta_{cm} = 146°$ of $d\sigma/d\Omega$ = 0.25 $\pm$ 0.10 nb/sr[129].

An extensive search for the reaction $dd \to {}^4\mathrm{He}\pi^0$ has been made at Saturne. The most recent experiment[130] reported a limit of 0.8 pb/sr (68% C.L.) at an incident deuteron energy of 800 MeV and around 100° cm. In a later publication[131] about the same experiment a differential cross section was reported of $d\sigma/d\Omega = 0.97 \pm 0.20 \pm 0.15$ pb/sr at $\theta_{cm} = 107°$ at an incident energy of 1.10 GeV, with the first error representing the statistical uncertainty and the second error the systematic uncertainty. This result would be the first to establish a differential cross section for π^0 production in the reaction $dd \to ^4$Heπ^0. The reaction $dd \to ^4$Heγ was measured simultaneously with π^0 production, leading to a differential cross section of $d\sigma/d\Omega = 0.82 \pm 0.18 \pm 0.10$ pb/sr at $\theta_{cm} = 110°$. We stress that the experiment is extremely difficult to execute and

to analyze. In particular, establishing unambiguously that the two photon events originated indeed in a π^0 from $dd \rightarrow {}^4\text{He}\pi^0$ is a major problem.

Wilkin[132] has used the measured $dd \rightarrow {}^4\text{He}\pi^0$ cross section along with an extrapolation of the $dd \rightarrow {}^4\text{He}\eta$ data and the Coon and Preedom external mixing model to determine an η-π^0 mixing angle which is compatible with other determinations reviewed in Ref. [6]. A consequence is significant (≈ 10 %) violations of charge independence in the ratio of the $pd \rightarrow {}^3\text{He}\pi^+$ and $nd \rightarrow {}^3\text{H}\pi^0$ cross sections at energies near the η production threshold.

3.4 Pion Scattering Experiments

Many attempts have been made to compare π^- and π^+ scattering from self-conjugate nuclei (isospin singlets). The first such an attempt was a comparison between the π^- and π^+ total cross sections for deuterium[133]. The authors used high statistics data with two targets of different lengths. The necessary Coulomb correction was simplified by the dominance of the single scattering term. The results were analyzed in terms of the energies and widths of the various Δ resonances. Some very reasonable results were obtained. The extracted Δ mass differences are consistent with those expected from the quark model.

The overriding uncertainty in many comparisons is in the removal of all effects related to the Coulomb interaction. Even if this is done precisely, many experiments are not sufficiently precise, in both statistics and systematics, to warrant a quantitative deduction of charge symmetry breaking effects. The early work on comparing the $\pi^\pm d$ total cross sections was followed by a series of measurements of the differences between the $\pi^- d$ and $\pi^+ d$ differential cross sections. Here an asymmetry parameter can be defined as,

$$A_\pi = \frac{(d\sigma/d\Omega)_{\pi^-} - (d\sigma/d\Omega)_{\pi^+}}{(d\sigma/d\Omega)_{\pi^-} + (d\sigma/d\Omega)_{\pi^+}}. \tag{37}$$

Multiple-scattering causes important effects in the angular distribution, except in the forward direction (where the Coulomb interaction is most important). This means that accounting for Coulomb interaction effects is a difficult task in a three-body Faddeev or any other calculation. Once this is done, the differences may be related to the differences in energies and widths of the various Δ resonances, as presented in Ref. [134]. However, as stated for instance by Köhler et al.[135], the errors on the values of A_π are in most cases of about the same size as the values of A_π themselves. Therefore, it is difficult to extract evidence for charge symmetry breaking.

A phase shift analysis of π^--^{4}He and π^+-^{4}He elastic scattering data was made by Brinkmöller and Schlaile[136] following the measurement of differential cross section angular distributions at a series of energies between 90 and 240 MeV[137]. For energies where both π^- and π^+ measurements exist, one can compare the phase shift solutions for A_π to the experimental charge asymmetry A_π. One finds that the treatment of Coulomb effects, as done in the phase shift analysis as the only origin for charge symmetry breaking, is adequate. Once more, intrinsic charge symmetry breaking

will only become transparent with more precise experimental data provided that concurrently a proper accounting of Coulomb effects can be made.

For π^- and π^+ elastic scattering from mirror nuclei (isospin doublets) a more promising approach is the determination of ratios of differential cross sections which can be combined into a super ratio. For the mirror nuclei ^{3}H and ^{3}He one can define two ratios

$$R_1 = \frac{d\sigma/d\Omega(\pi^- \, {}^3H)}{d\sigma/d\Omega(\pi^+ \, {}^3He)} \ , \ R_2 = \frac{d\sigma/d\Omega(\pi^- \, {}^3He)}{d\sigma/d\Omega(\pi^+ \, {}^3H)}. \tag{38}$$

Clearly in the absence of Coulomb effects charge symmetry requires $R_1 = R_2 = 1$. The ratios R_1 and R_2 allow the determination of a super ratio $R = R_1/R_2$, an experimental quantity independent of calibrations of beam intensity and target thickness, which can be arranged to be also independent of detector inefficiencies. Any deviation of R from the value 1.00 indicates charge symmetry breaking. Significant deviations from 1.00 have been measured[138] which were explained in terms of direct and indirect Coulomb effects[139]. The latter include small differences in the ^{3}H and ^{3}He wave functions: differences in the odd nucleon radii and the even nucleon radii for this pair of mirror nuclei. The numerical values are in qualitative agreement with predictions obtained from solving the Faddeev equations.

3.5 Pion Reaction Experiments

A comparison of the reactions $\pi^- d \to nn\pi^0$ and $\pi^+ d \to pp\pi^0$, as well as $\pi^- d \to nn\eta$ and $\pi^+ d \to pp\eta$ leads to the following ratios of the triple differential cross sections

$$R_1 = \frac{d^3\sigma(\pi^- d \to nn\pi^0)}{d^3\sigma(\pi^+ d \to pp\pi^0)} \tag{39}$$

and

$$R_2 = \frac{d^3\sigma(\pi^- d \to nn\eta)}{d^3\sigma(\pi^+ d \to pp\eta)}. \tag{40}$$

Charge symmetry requires that both ratios R_1 and R_2 are equal to one for all incident pion energies and for every angle of the scattered meson. However, the np mass difference and the Coulomb interaction will cause charge symmetry breaking. Additional breaking will result from differences in the $n\eta$ and $p\eta$ interactions and from π^0-η mixing. An experiment to measure the ratios R_1 and R_2 is in progress at the AGS of BNL[140]. One of the challenges for a successful completion of the experiment is to account for any differences in the π^- and π^+ incident beams.

3.6 Breakup Reactions and Other

a) $^4He(\gamma, p)$ and $^4He(\gamma, n)$

Comparisons between the differential cross sections for the ^{4}He(γ,p) and ^{4}He(γ,n) reactions are a test of charge symmetry provided the photon absorption proceeds purely by an E1 transition. Lately results have been published on the absolute cross section of the ^{3}He(n,γ) reaction for five energies between 0.14 and 2.0 MeV to an accuracy of about $\pm 10\%$[141]. These results together with other ^{3}He(n,γ) capture data applying detailed balance, and ^{4}He(γ,n) photo-disintegration data, if compared with ^{4}He(γ,p) data show that the ratio of the photo-disintegration cross sections $R_\gamma = \sigma[^4\mathrm{He}(\gamma,p)]/\sigma[^4\mathrm{He}(\gamma,n)]$ is equal to $\sim$1.1 over the resonance region. This ratio is also given by conventional theories which leave out explicit charge symmetry breaking nucleon-nucleon interactions. Consequently the controversies stemming from the comparisons of the ^{4}He(γ,n) and ^{4}He(γ,p) reactions may now have been resolved. Indeed, a new measurement of the (γ,p) and (γ,n) differential yields at 90° for the two-body photodisintegration of ^{4}He has now been reported[142]. Using tagged photons of energies between 25 and 60 MeV, data were obtained for both channels simultaneously using windowless $\Delta E - E$ telescopes to detect the ^{3}H and ^{3}He recoil particles. The ratio of the angle integrated yields, which is insensitive to many systematic errors due to the simultaneous measurement in the same detectors, agrees with the results of calculations[143] which take into account only charge symmetric nucleon-nucleon interactions. Unfortunately, it will be extremely difficult to perform the experiment and carry out the analysis to a precision sufficient for a quantitative deduction of charge symmetry breaking effects.

Measurements of two-body photodisintegration of ^{4}He at higher energies (in the energy range 100 to 360 MeV), detecting the recoiling ^{3}He, respectively ^{3}H nuclei, show ratios R within 30% of unity at all angles with slightly greater values at the higher photon energies. In view of the errors of the individual data points, the result is not inconsistent with a ratio of unity[144].

b) $^2H(\vec{d},pn)d$ and $^2H(\vec{d},np)d$

In a recent publication[145] a novel probe of charge symmetry breaking was reported involving single deuteron breakup in polarized dd scattering: $\vec{d}d \to dpn$. In the first phase of the experiment the spin observables A_y, A_{yy} and A_{zz} are compared for the mirror reactions ^{2}H$(\vec{d},dp)n$ and ^{2}H$(\vec{d},dn)p$ at two angle pairs: $(\theta_d,\phi_d,\theta_N,\phi_N) = (17.0°, 0°, 17.0°, 180°)$ and $(17.0°, 0°, 34.5°, 180°)$. The incident energy is rather low so the unwanted effects of the Coulomb interaction are expected to be large.

Thus the comparison of dp and dn coincidence data under identical kinematical conditions serves to check the influence of the Coulomb interaction. Only for the angle pair $(17.0°, 0°, 34.5°, 180°)$ is there a statistically significant difference in the measured values for A_{zz} (0.060$\pm$0.025 between the dp and dn A_{zz} data). In the second phase of the experiment the reaction ^{2}H$(\vec{d},pn)d$ was measured at $(\theta_p,\phi_p,\theta_n,\phi_n) = (17.0°, 0°, 17.0°, 180°)$. In this case if charge symmetry holds then A_{yy} and A_{zz} along the kinematic locus in a plot of T_p versus T_n should be symmetric with respect to the $T_p = T_n$ point and A_y should be antisymmetric with respect to this equal energy point. The result indicates that A_{yy} and A_{zz} are indeed symmetric to within their

statistical uncertainties of ± 0.025, while A_y is antisymmetric to within their statistical uncertainties of ± 0.016. Only when taking restricted energy intervals may there be an indication of charge symmetry breaking. Clearly this new method has promise provided the incident energy is increased, in order to be more certain about the effects of the Coulomb interaction, together with an improved statistical accuracy.

4. Summary and Suggested Further Work

Charge independence and charge symmetry breaking is caused by the d-u quark mass difference $m_d - m_u > 0$, along with electromagnetic effects. The consequences of these effects can be manifest by including their imprint on hadronic matrix elements or by using quark models directly. Lattice QCD calculations are not yet sufficiently accurate to handle small differences between the small masses of current quarks.

The general goal of this area of research is to find small charge independence and charge symmetry breaking effects, and then explain these in terms of fundamental ideas. Over the years there has indeed been substantial experimental and theoretical progress, which we now summarize briefly. First, we recall the idea that $m_d - m_u > 0$ accounts for the observed mass differences between members of hadronic isospin multiplets. Next we note that charge independence breaking in the $^1S_0$ system is well explained in terms of meson exchange models. The most significant effect is the 4.6 MeV mass difference between charged and neutral pions, which has its ultimate origin in the Coulomb interaction amongst the quarks. The effects of $\gamma\pi$ exchange are also relevant.

Substantial effects of ρ^0-ω mixing have been observed in the $e^+e^- \rightarrow \pi^+\pi^-$ cross section at $q^2 \approx m_\omega^2$. The results allow an extraction of the strong contribution to the ρ^0-ω mixing matrix element $< \rho^0|H_{str}|\omega > \approx$ - 5200 MeV^2. Two nucleons may exchange a mixed ρ^0-ω meson. If one uses $< \rho^0|H_{str}|\omega > \approx$ - 5200 MeV^2 one obtains a nucleon-nucleon interaction which accounts for $\Delta a_{CSB} = a^N_{pp} - a^N_{nn} = 1.5 \pm 0.5$ fm. Such a force also is responsible for most of the strong interaction contribution to the ^{3}H-^{3}He binding energy difference and accounts for much of the Nolen-Schiffer anomaly. More generally, the use of potentials consistent with Δa_{CSB} and Δa_{CD} accounts for formerly anomalous binding energy differences in mirror nuclei and in analog states.

The TRIUMF (350 and 477 MeV) and IUCF (183 MeV) experiments have compared analyzing powers of $\vec{n}p$ and $n\vec{p}$ scattering and observe charge symmetry breaking at the level expected from π, γ and ρ^0-ω exchange effects. The latter effects are important at 183 MeV.

The virtual mesons of nucleon-nucleon potentials have space-like four-momenta, while the ρ^0-ω mixing matrix element has been extracted for on-shell vector mesons. Several authors have postulated significant off-shell effects that essentially wipe out the effects of ρ^0-ω mixing in nucleon-nucleon interactions. However, these ideas seem to contradict the feature that the $\gamma\rho$ or $\gamma^*\rho$ transition matrix element is observed to be approximately independent of the photon four momentum.

Charge symmetry breaking has also been studied in hypernuclear systems and the

spin dependence of the ΛN interaction has been extracted from the observed masses of the ground and first excited state.

4.1 Suggested Experimental Investigations

Experimental searches for charge independence and charge symmetry breaking are difficult, time consuming tasks. So the first order of business is to encourage the ongoing experiments. Thus we look forward to the complete analysis of the TRIUMF comparison of neutron and proton analyzing powers in np elastic scattering at 350 MeV. The reaction $\pi^- d \to \gamma nn$ is the principle source of information on low energy nn scattering. Thus we anticipate the the analysis of the data taken in the new TRIUMF measurement. The asymmetry about 90° in the angular distribution of the $np \to d\pi^0$ reaction would provide information about π^0-η mixing and we encourage a precision experiment. A BNL comparison of the reactions $\pi^- d \to nn\pi^0$ and $\pi^+ d \to pp\pi^0$, as well as $\pi^- d \to nn\eta$ and $\pi^+ d \to pp\eta$ would allow a new study of the difference between the nn and pp interactions as well as π^0-η mixing. We also encourage the extension of the ^{2}H$(\vec{d}, pn)d$ and ^{2}H$(\vec{d}, np)d$ measurements to higher energies.

Next we discuss possibilities for improving earlier experiments and some new ones. A clear observation of a non-zero value of the $dd \to ^4$Heπ^0 cross section would provide a definite manifestation of charge symmetry breaking. One needs to learn how to handle the background from the $dd \to ^4$Heγ reaction. More precise data for $\pi^\pm$ - ^{3}He (^{3}H) elastic scattering would allow a more precise determination of the difference between the even and odd radii. The masses of the hypernuclei should be re-examined and determined more precisely. We have been mainly concerned with nuclear effects, but also stress that the effects of Λ-Σ^0 mixing could be observed by comparing the weak decay rates for $\Sigma^+ \to \Lambda e^+ \nu_e$ and $\Sigma^- \to \Lambda e^- \bar{\nu}_e$.

4.2 Suggested Theoretical Explorations

There are a number of tasks which can be readily accomplished with existing techniques. The $\gamma\pi$ exchange potential should be re–evaluated, especially its consequences for the spin–dependent neutron–proton scattering. The role of vector meson mixing for charge symmetry breaking ΛN scattering should be re-examined. Careful evaluations of the effects of the different densities seen by valence neutrons and protons should be included in QCD sum rule evaluations of the medium modifications to the neutron-proton mass difference. Realistic charge dependent and charge asymmetric potentials should be used in shell model calculations; this awaits a more complete evaluation of the $\gamma\pi$ exchange potential. The scattering theory for pion interactions with ^{3}He (^{3}H) could be made more precise so as to better learn about charge symmetry violations in the wave functions. The role of Coulomb effects in the π deuteron total cross section should be re-assessed to confirm the conclusions of the original experiment. The effects of charge symmetry breaking in the π^0-nucleon interaction on the $np \to d\pi^0$ angular distribution should be estimated. Similarly one should make careful predictions for the $\pi d \to NN\pi^0$ and $\pi d \to NN\eta$ reactions.

There are also some more challenging tasks. One is to find a precise method to

determine the charge dependence of meson-nucleon coupling constants. Present data limits such effects to less than about 1%, which would allow significant effects. The off-shell dependence of ρ^0-ω mixing should be determined in a definitive way. We have argued here that a significant q^2 variation contradicts many experiments involving $\gamma\rho$ transitions for real and virtual photons. But it would be interesting to see if a model with significant off-shell dependence in the ρ^0-ω mixing could be consistent with those experiments. We have discussed above explanations of the Nolen–Schiffer anomaly which involve both vector and scalar effects. The vector explanations seem closely related to two-nucleon data and therefore more likely correct. However, scalar effects are surely present. It would be useful to devise theoretical and experimental means to separate and distinguish the two categories of explanation. In either case, the ultimate origin of the anomaly is the mass difference between up and down quarks.

This quark mass difference, $m_d - m_u$ seems to be related to a large variety of phenomena in particle and nuclear physics. Most of the effects are well understood. Perhaps the next relevant question is why are there two light quarks with a slightly different mass?

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